

AFRL-AFOSR-UK-TR-2013-0015



Planar Droplet Sizing in Dense Sprays

Professor Yannis Hardalupas

**Imperial College of Science Technology and Medicine
Exhibition Road
London, United Kingdom SW7 2BT**

EOARD Grant 12-2011

Report Date: April 2013

Final Report from 01 March 2012 to 28 February 2013

Distribution Statement A: Approved for public release distribution is unlimited.

**Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 8 April 2013		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) 1 March 2012 – 28 February 2013	
4. TITLE AND SUBTITLE Planar Droplet Sizing in Dense Sprays				5a. CONTRACT NUMBER FA8655-12-1-2011	
				5b. GRANT NUMBER Grant 12-2011	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Professor Yannis Hardalupas				5d. PROJECT NUMBER	
				5d. TASK NUMBER	
				5e. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Imperial College of Science Technology and Medicine Exhibition Road London, U} 207 2BT				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD Unit 4515 BOX 14 APO AE 09421				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR/IOE (EOARD)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-UK-TR-2013-0015	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution A: Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT An investigation was undertaken to examine the application of a laser beam scanning methodology on the measurement of the time-averaged spray spatial structure. This approach can directly reduce secondary light scattering effects from the spray droplets and can take into account probe laser beam and scattered light intensity attenuation in order to reduce associated uncertainties on the spray characteristics. Evaluation of two approaches was performed, where one considered scanning the probe laser beam across the spray and the other considered traversing the spray while the probing beam and the imaging optics were fixed. It is determined that for the purposes of evaluating the methodology for correcting quantitative measurement errors due to attenuation, the second approach is more appropriate. This is because scanning the beam would require constant refocusing of the imaging system to the probed region. Another issue is the changing imaging resolution as the distance between the probe laser beam and the imaging optics is constantly changing. By traversing the spray across the probe beam, both of the aforementioned effects are eliminated and the signal correction methodology can be applied directly. The scattered light intensity correction methodology was successfully applied to a flat spray with measurements close to the nozzle and beam probing along the long dimension of the spray, so that attenuation effects are more profound. It is determined that attenuation of the laser beam along the spray can be as high as 20% and attenuation of the measured intensity signal can exceed 10%. Corrections can be made to address the attenuation effects and in the investigated spray the measurement error exceeds 10% especially at the regions of the spray further along the laser beam, where attenuation is strongest. This highlights the need for accounting for the attenuation effects of the laser beam and scattered light intensity for quantitative spray measurements.					
15. SUBJECT TERMS EOARD, Metrology, Laser Induced Fluorescence, Aerosol Detection					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 28	19a. NAME OF RESPONSIBLE PERSON Kevin P. Bollino, Lt Col, USAF
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)1895 616163

FINAL REPORT

AWARD N°: FA8655-12-1-2011
TITLE: Planar Droplet Sizing in Dense Sprays
INVESTIGATOR: Professor Y. Hardalupas
ORGANISATION: Imperial College of Science, Technology and Medicine

REPORTING PERIOD: From: 1 March 2012
To: 28 February 2013
PROJECT START DATE: 1 March 2012
DATE OF ISSUE OF THIS REPORT: 8 April 2013

ADMINISTRATIVE OFFICE: European Office of Aerospace
Research and Development
(EOARD)

GOVERNMENT PROGRAM MANAGER: Dr. Kevin P. Bollino

Table of Contents

Table of Contents	2
List of Symbols, Abbreviations and Acronyms	3
List of figures	4
Summary	5
Introduction	6
Experimental setup	8
Data Processing methodology	14
Results	18
Summary of findings	24
References	25

List of Symbols, Abbreviations and Acronyms

I_0	Intensity of the laser beam before it enters the spray
e_b	Relative decrease of the laser beam intensity as it traverses the spray
e_c	Relative decrease of the scattered light intensity as it traverses the spray
ILIDS	Interferometric Laser Imaging Droplet Sizing, ILIDS
K	Calibration constant
LIF	Laser induced fluorescence
PDV	Phase Doppler Velocimetry
SMD	Sauter mean diameter
σ or J_s	scattering cross section of the droplets

List of figures

Figure 1: An example of a laser beam scanning system.....	9
Figure 2: Traversing the spray through a fixed laser beam. The spray is the only moving component.	9
Figure 3: Flat spray air assist atomiser mounted on the linear traverse. The spray centreline is shown as a white dashed line and the approximate boundaries are shown in solid white lines.	11
Figure 4: Pressure vessel for the continuous pumping of the sprayed liquid.	11
Figure 5: Motorised linear traverse stage used to traverse the spray along the laser probe beam.....	12
Figure 6: Complete experimental arrangement showing the mounted atomiser, the laser power meter, the beam steering optical arrangement and the beam path (dashed green line). The location of measurement is the solid green line just below the spray	13
Figure 7: Scanning the first line of the spray. There are no droplets between the probe beam and the camera so there is no attenuation of the measured scattered light intensity.....	15
Figure 8: Scanning of the spray. During scanning of the first line there is no interference between the laser beam and the detector	18
Figure 9: Spatial distribution of scattered light intensity across the spray for the first scanned beam. Spray centreline is at X=600px	18
Figure 10: Spatial distribution of the extinction coefficient e_b across the spray for the first scanned beam. Spray centreline is at X=600px.....	19
Figure 11: Spatial distribution of the scattering coefficient σ across the spray for the first scanned beam. Spray centreline is at X=600px.....	19
Figure 12: Spatial distribution of the attenuation coefficient e_c across the spray just after the first scanned beam. Spray centreline is at X=600px	19
Figure 13: Spatial distribution of the attenuation coefficient e_c across the spray just before the last scanned beam. Spray centreline is at X=600px	21
Figure 14: Spatial distribution of scattered light intensity across the spray for the last scanned beam. Spray centreline is at X=600px	21
Figure 15: Spatial distribution of the corrected scattered light intensity across the spray for the last scanned beam. Spray centreline is at X=600px	21
Figure 16: Spatial distribution of the corrected scattering coefficient σ across the spray for the last scanned beam. Spray centreline is at X=600px	21
Figure 17: Spatial distribution of the uncorrected scattering coefficient σ across the spray for the last scanned beam. Spray centreline is at X=600px	22
Figure 18: Extinction coefficient along the spray plane.	22
Figure 19: Attenuation coefficient along the spray plane.....	22
Figure 20: Corrected scattering coefficient along the spray plane.	22
Figure 21: Uncorrected scattering coefficient along the spray plane.	23
Figure 22: Correction of scattering coefficient along the spray plane.....	23

Summary

When imaging dense sprays the acquired measurements are hindered optical noise due to multiple scattering from droplets, attenuation of the laser beam as it traverses the spray and attenuation of the recorded intensity signal due to droplets present between the probed spray region and the detector. For this reason an investigation was performed to assess the possibility of addressing these issues by scanning a laser beam across the spray instead of illuminating with a laser sheet. Two scanning methods were considered. Scanning the laser beam through the spray and traversing the spray along a fixed laser beam. The second method was selected as it has the benefits of keeping the distance between the laser probe beam and the imaging camera always constant and consequently does not require constant refocusing of the camera and correction for the changing of the imaging resolution of the laser beam scanning approach. Following the choice of the scanning approach, a high precision opto-mechanical arrangement was built to allow intensity measurements of scattered light across a flat spray cross section to be used for applying correction procedures for the attenuation of the probing and collected light. The correction procedure described by Brown, McDonnell et al. (2002) was selected and implemented in MATLAB. Application of the correction methodology on scattered light intensity profiles across a plane of the spray provided quantitative measurements of the intensity attenuation along the beam path, of the attenuation of the scattered light intensity between the probed spray region and the imaging camera and the scattering cross section of the spray droplets. From the above the full cross section of the spray was reconstructed in terms of the scattering cross section, which is representative of the droplet surface area density. The reconstructed spray shape was representative of a flat spray, elliptical and symmetric along the two normal axes, which demonstrates that the developed approach was appropriate.

Introduction

A planar droplet sizing technique (also known as optical patternator) has been proposed for the measurement of the Sauter mean diameter (SMD) of spray droplets, based on combined laser-induced fluorescence and scattered light (LIF/Mie) intensity imaging on a plane of a spray determined by a laser sheet (Yeh, Kosaka et al. 1993; Kamimoto 1994; Le Gal, Farrugia et al. 1999; Sankar, Maher et al. 1999; Domann and Hardalupas 2001; Domann and Hardalupas 2003; Zimmer, Domann et al. 2003; Charalampous and Hardalupas 2011a; Charalampous and Hardalupas 2011b). The LIF/Mie technique has a significant advantage over other droplet sizing methods in that it is a planar technique that can size full planes of sprays, while the other methods are limited to “point” (Phase Doppler Velocimetry, PDV), line of sight (laser diffraction), or planes of small cross-sectional areas (Interferometric Laser Imaging Droplet Sizing, ILIDS) of sprays. In addition, this technique is applicable to dense spray regions, provided that appropriate compensation of multiple scattering effects and laser intensity attenuation along the sprays is included.

The fundamental hypothesis of the LIF/Mie technique for droplet sizing (Yeh, Kosaka et al. 1993; Kamimoto 1994) is that when a spherical droplet doped with a fluorescing dye is illuminated with a laser, the intensity of the fluorescent light from a droplet is proportional to the volume of the illuminated droplet while the intensity of the scattered light is proportional to the surface area of the illuminated droplet. However, it has been shown that the above assumption is not always valid (Domann and Hardalupas 2001; Domann and Hardalupas 2001; Domann, Hardalupas et al. 2002; Domann and Hardalupas 2003; Charalampous and Hardalupas 2011a; Charalampous and Hardalupas 2011b) and there is a need to develop appropriate processing for appropriate sizing of droplets (Domann and Hardalupas 2001). Recently, an extensive analysis of the operation of the LIF/Mie technique (Charalampous and Hardalupas 2011a; Charalampous and Hardalupas 2011b) has led to the development of a novel approach to improve the sizing accuracy of the technique.

However, the application of the technique in dense sprays can lead to multiple scattering on the spray droplets outside the illuminated plane (Czerwinski, Mroczka et al. 2001; Czerwinski, Mroczka et al. 2001; Berrocal, Meglinski et al. 2005). This may lead to a qualitative change of the measured spatial distribution of the droplets in

sprays and uncertainties in the measurement of the droplet Sauter Mean Diameter. As a consequence, two methods have been proposed to correct for the effects of multiple scattering and laser incident beam intensity attenuation during propagation through the sprays (Brown, McDonnell et al. 2002; Berrocal, Kristensson et al. 2008). The method of Berrocal, Kristensson et al. (2008) is more complicated and more expensive to apply and the current proposal intends to implement the method of Brown, McDonnell et al. (2002) to correct for the two effects in dense sprays by setting up an optical scanning laser beam system and appropriate imaging. Measurements with the scanning system and subsequent correction will allow the evaluation of the importance of the multiple scattering and laser beam attenuation and quantify the resulting uncertainties in dense sprays.

Experimental setup

There are several approaches to scan a laser beam through a plane of a spray. An example of a scanning approach is shown in **Figure 1**, which has the potential to achieve fast scanning, as reported by Edwards et al. (2003). It makes use of two off-axis parabolic mirrors, one on the transmission and one on the receiving side, and a fast scanning mirror and driver. The principle of this approach is to simulate a point source placed at the focal point of the transmitting off-axis parabolic mirror, so that the laser beam would be reflected always along the same direction, creating a movement of translation of the beam as the mirror is rotating. The collection of the translated beam is performed with the same principle, using a photo-detector placed at the focal point of the off-axis parabolic mirror. As a consequence, the laser beam attenuation during propagation through different locations in the spray can be measured with one detector. Scanning mirrors with speeds above 1 kHz are available, which would be appropriate for the realisation of the fast scanning laser beam system. This approach is rather complicated and high speed measurements are not required for the current investigation. It is, however, possible that this scanning approach may lead to instantaneous measurements in sprays, provided that the current investigation demonstrates that the scanning approach is effective in correcting the optical issues present in dense sprays.

Instead of scanning the laser beam through the spray, the spray can be mounted on a motorised linear stage and traversed along a laser beam fixed in space (**Figure 2**). The spray traversing approach is equivalent to the beam scanning approach for the purposes of this experiment. The laser beam scanning approach has the disadvantage that is more complex to setup and that as the laser beam is scanned through the spray the distance between the laser beam and the camera changes. This requires constant refocusing of the camera lens during the duration of the experiment, which is both inconvenient and changes the magnification of the imaging system, which also needs to be accounted for. Alternatively, the camera can be mounted on a linear stage and move together with the scanning beam so that the focal distance and the system magnification remain constant but this approach is difficult to implement. The spray traversing approach has the advantage that the imaging system needs to be focused only once and the system magnification is always fixed, while the system mechanics

are simplified. In addition no parabolic optics are required for this approach as the beam is not moving. For these reasons the spray traversing method was preferred for the current experiment. A summary of the advantages and disadvantages of the two approaches is given in Table 1.

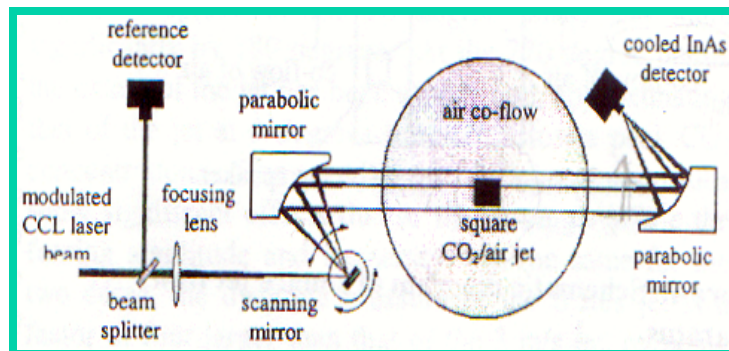


Figure 1: An example of a laser beam scanning system.

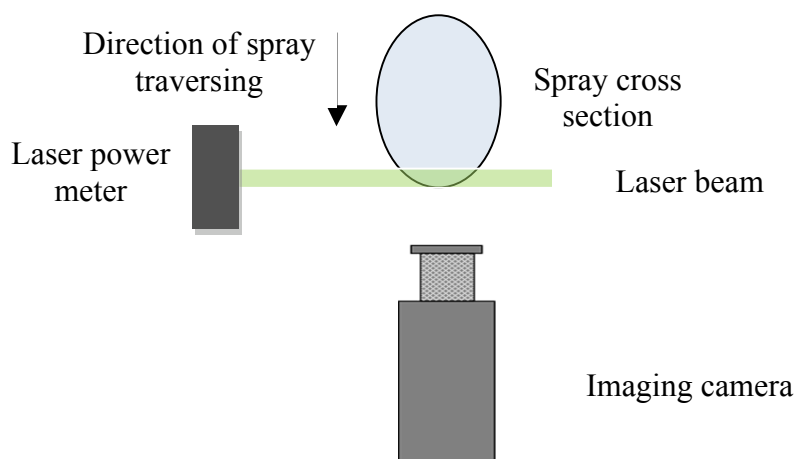


Figure 2: Traversing the spray through a fixed laser beam. The spray is the only moving component.

Table 1: Comparison between beam scanning and spray traversing		
	Advantages	Disadvantages
Beam Scanning	<ul style="list-style-type: none"> • Spray is fixed in space. • Fast beam scanning is possible. 	<ul style="list-style-type: none"> • Need to constantly refocus camera during measurement. • Need to account for changing optical resolution during scanning • Complex optical arrangement
Spray traversing	<ul style="list-style-type: none"> • Optical system always in focus. • Optical resolution constant throughout measurement. • Simple optical arrangement 	<ul style="list-style-type: none"> • Measurement duration is slower than beam scanning.

For the purpose of this investigation, a flat spray air assist atomiser (**Figure 3**) with independent adjustment of the liquid and gas flowrates was used. This allows for fine control of the spray droplet size and number density. For example, by increasing the air flow rate, while maintaining the same liquid flow rate a greater number of smaller droplets is produced and vice versa. The overall spatial distribution of the spray is largely independent of the fluid flowrates. The atomiser was mounted vertically with the tip exhausting downwards, so that the injected liquid could be easily collected. The atomised liquid was distilled water. For the pumping of the water a 9l vessel (**Figure 4**) was utilised where the contained water was kept under constant pressure of 4bar stabilised by a pressure regulator. The large capacity of the vessel assured uninterrupted water flow for over 2 hours and the fixed pumping pressure guaranteed that the water flowrate did not fluctuate. The atomising gas was compressed nitrogen from a 20l cylinder, delivered at the system at a pressure fixed at 4bar by pressure regulator. The air and water flowrates were monitored by rotameters. The above arrangement guaranteed the continuous operation of the spray with stable characteristics over time periods sufficiently longer than the time required for complete characterisation of a full spray plane.

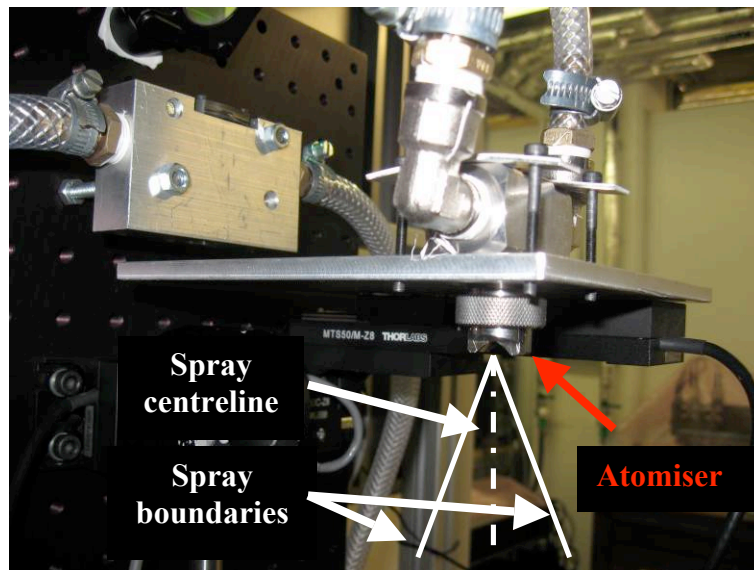


Figure 3: Flat spray air assist atomiser mounted on the linear traverse. The spray centreline location is shown as a white dashed line and the approximate location of the spray boundaries are shown in solid white lines.



Figure 4: Pressure vessel for the continuous pumping of the sprayed liquid.

Spray measurements were performed along the horizontal plane at a distance of 20mm downstream of the atomiser nozzle. At this location, the spray is sufficiently

dense for measurable attenuation of the illuminating beam and the collected signal. The illuminating beam was produced by a Nd:YAG laser operating at wavelength 532nm. The diameter of the laser beam was 4.5mm. Absorption of this wavelength by water is minimal, so only the scattering of the illuminating light needs to be considered in the data processing method. Imaging of the scattered light from the spray was performed by a 12bit CCD camera (Model PCO sensical QE). The camera was fitted with a 105mm lens coupled with an interference filter. The interference filter was centred at 532nm and had a bandwidth of 10nm which suppressed ambient light noise for improved accuracy in the measurements. Monitoring of the intensity of the laser beam before and after the spray was performed using a laser power meter. The motorised linear stage was acquired from Thorlabs MTS50 models (**Figure 5**). The positioning accuracy of each stage is within 1 μ m. The travel range of each stage was 50mm which is sufficient to traverse the full spray across the laser beam for many planes past the atomiser exit. The spray was traversed at increments of 5mm at a time. In this way, the speed of the measurements was maximised while the spray was fully resolved. The complete optical setup is presented in **Figure 6**. For each increment, 1000 images were acquired which are sufficient for the spray characteristics to converge.



Figure 5: Motorised linear traverse stage used to traverse the spray along the laser probe beam

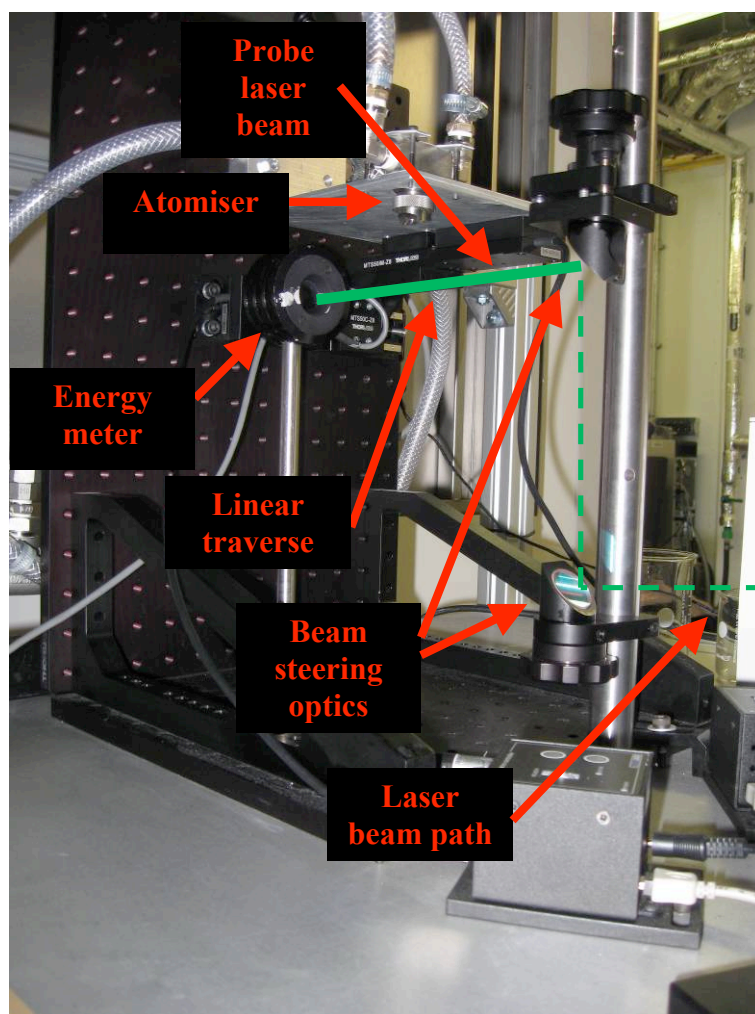


Figure 6: Complete experimental arrangement showing the mounted atomiser, the laser power meter, the beam steering optical arrangement and the beam path (dashed green line). The location of measurement is the solid green line just below the spray

Data Processing methodology

When considering processing the dense spray images, attenuation effects of the incident laser beam have to be taken into account. There are three effects to be considered:

1. Attenuation of the laser beam intensity as it traverses through the spray.
2. Attenuation of the scattered light intensity as it propagates from the illuminated droplets to the detector
3. Multiple scattering of the scattered light initiated from one droplet on other droplets in the spray

These have been considered by many researchers and various approaches have been proposed to address them as the measurement accuracy of the LIF/Mie technique (Yeh, Kosaka et al. 1993; Sankar, Maher et al. 1999) is sensitive to the scattered light intensity (Charalampous and Hardalupas 2011a; Charalampous and Hardalupas 2011b; Charalampous and Hardalupas 2012).

Approaches for addressing the first effect include bidirectional illumination (Su, Drake et al. 1998), measurement of the amount of attenuation of the LIF signals by means of a laser dye cuvette and compensation for the attenuation (Sick and Stojkovic 2001), sequential illumination by opposed laser sheets (Douglas, Verdick et al. 1996). In order to address the latter issue, multiple imaging of the spray under structured illumination methods have been proposed (Berrocal, Kristensson et al. 2008; Kristensson, Araneo et al. 2011; Kristensson, Berrocal et al. 2011; Kristensson, Berrocal et al. 2011; Berrocal, Kristensson et al. 2012). However, these methods are very complex and require substantial investment of resources and effort.

A simpler yet efficient method that addresses all effects has been proposed by Brown, McDonnell et al. (2002). Instead of using a laser sheet to illuminate the spray, a laser beam is used. Since a smaller number of droplets are illuminated with the laser beam at a time rather than the laser sheet, there are less multiple scattering affects and the collected light is inherently substantially less affected by optical noise. The quantitative description of the attenuation effects of the light collected by the spray is considered by Eq. (1) below:

$$I_{CCD}(x, z) = K(z) \cdot I_0 \cdot e_b(x, z) \cdot \sigma(x, z) \cdot e_c(x, z) \quad (1)$$

where:

- I_0 is the incident intensity of the laser beam before it enters the spray
- $e_b(x,z)$ is the relative decrease of the laser beam intensity as it traverses the spray
- $\sigma(x,z)$ is the scattering cross section of the droplets
- $e_c(x,z)$ is the relative decrease of the scattered light intensity as it traverses the spray
- K is a constant that translates the intensity signal detected by the camera to the physical laser intensity

The procedure for the reconstruction of the spray is applied in steps which reconstruct the spray one layer at a time. The method begins with the evaluation of the constant K which is estimated as:

$$K(z) = \frac{\int_{x=-\infty}^{+\infty} \frac{I_{CCD}(x,z)}{e_c(x,z)} \cdot dx}{1 - e_b(+\infty, z)} \quad (2)$$

For the first scanned beam, there is no attenuation of the scattered light signal on the droplets, as is schematically shown in **Figure 4**. Hence Eq. (2) reduces to:

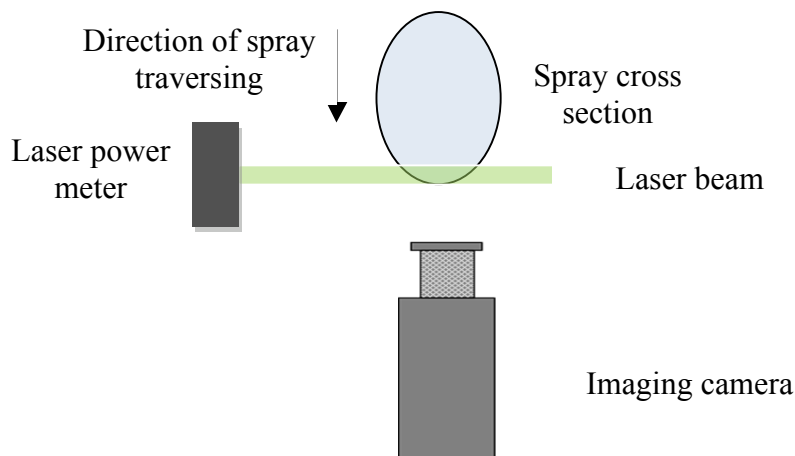


Figure 7: Scanning the first line of the spray. There are no droplets between the probe beam and the camera so there is no attenuation of the measured scattered light intensity.

$$K(0) = \frac{\int_{x=-\infty}^{+\infty} I_{CCD}(x, 0) \cdot dx}{1 - e_b(+\infty, 0)} \quad (3)$$

and is completely solvable from the measured quantities.

Once K is estimated, it is possible to estimate $e_b(x, z)$ as:

$$e_b(x, z) = 1 - \frac{1}{K(z)} \cdot \int_{x=0}^{x=x} \frac{I_{CCD}(x, z)}{e_c(x, z)} \cdot dx \quad (4)$$

For the first scanned beam, the above equation becomes

$$e_b(x, 0) = 1 - \frac{1}{K(0)} \cdot \int_{x=0}^{x=x} I_{CCD}(x, 0) \cdot dx \quad (5)$$

Subsequently $\sigma(x, z)$ is evaluated as:

$$\sigma(x, z) = \frac{I_{CCD}(x, z)}{K(x, z) \cdot e_b(x, z) \cdot e_c(x, z)} \quad (6)$$

and as before, for the first scanned beam, Eq. (6) reduces to:

$$\sigma(x, 0) = \frac{I_{CCD}(x, 0)}{K(x, 0) \cdot e_b(x, 0)} \quad (7)$$

In order to determine the spray quantities for the first scanned beam, all the information needed is available. However, for scanned beams further inside the spray, where attenuation of the scattered light by the spray droplets is present, consequential knowledge of $e_c(x, z)$ is required. This is obtained from:

$$e_c(x, z) = e^{-\int_{z=0}^{z=z} \sigma(x, z) \cdot dz} \quad (8)$$

following the Beer-Lambert law.

Therefore, all the required information for the evaluation of the spray characteristics from one scanned beam further inside the spray is available and can be obtained by following equations (2) to (8).

Results

From the imaging measurements of the spray, the average distribution of the scattered light intensity was evaluated. For the first scanned beam, where there is little to no attenuation from preceding droplets, the profile is presented in Figure 9 below. The direction of the laser beam is from the left to the right. The scattered light intensity distribution is symmetric and there is a maximum in the middle of the spray where the droplet optical density is highest.

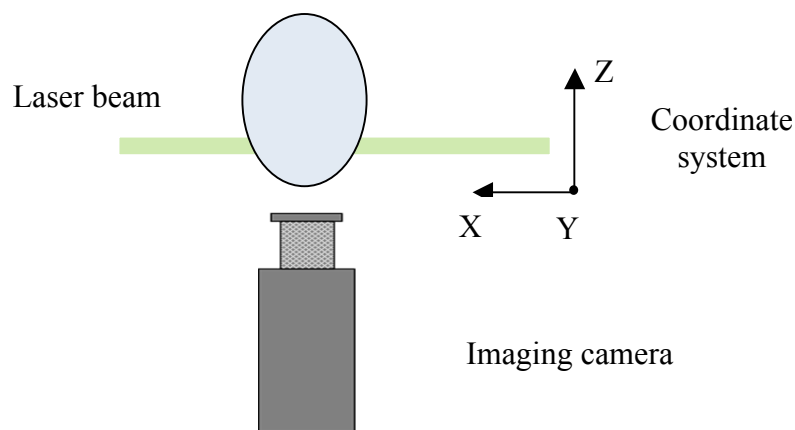


Figure 8: Scanning of the spray. During scanning of the first line there is no interference between the laser beam and the detector

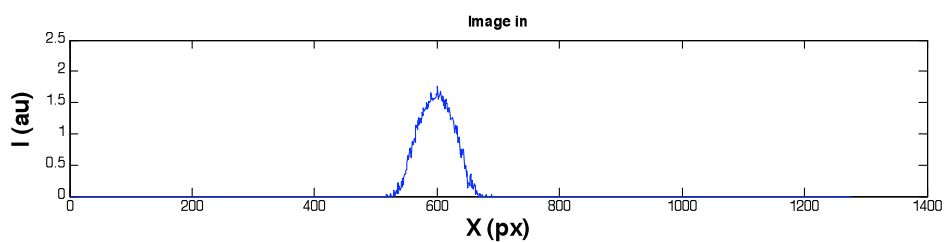


Figure 9: Spatial distribution of scattered light intensity across the spray for the first scanned beam. Spray centreline is at X=600px.

The attenuation of the laser beam is shown in **Figure 10** and it is contained within the region where the incident light is scattered.

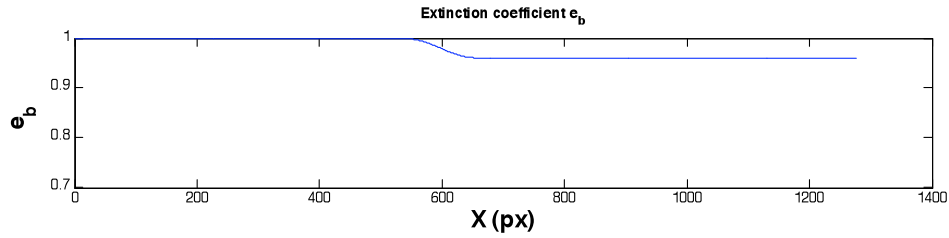


Figure 10: Spatial distribution of the extinction coefficient e_b across the spray for the first scanned beam. Spray centreline is at $X=600\text{px}$

The scattering coefficient, as evaluated from eq. (7), is shown in **Figure 11** and it resembles the profile of the scattered light intensity. This is reasonable since the intensity of the scattered light is proportional the scattering cross section of the spray.

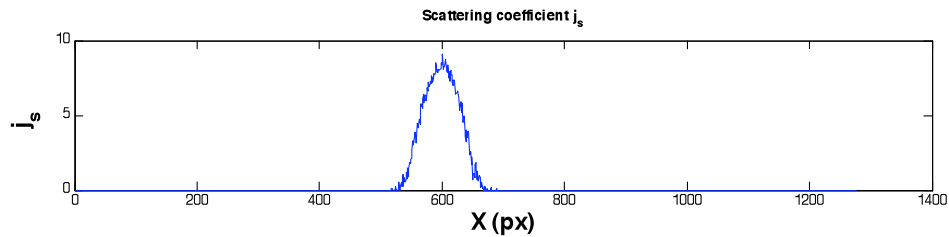


Figure 11: Spatial distribution of the scattering coefficient σ across the spray for the first scanned beam. Spray centreline is at $X=600\text{px}$

Past the first scanned beam, there is attenuation of the scattered light intensity signal from droplets within the spray due to the optical density of the spray droplets. This is calculable from eq. (8) for the first scanned line and it is presented in **Figure 12**. Since this attenuation will affect quantitative spray measurements, it is accounted for when the spray characteristics deeper inside the spray are probed with the scanning system.

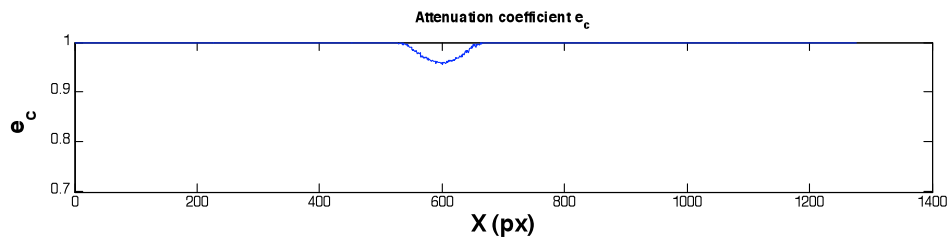


Figure 12: Spatial distribution of the attenuation coefficient e_c across the spray just after the first scanned beam. Spray centreline is at $X=600\text{px}$

The correction procedure progresses in the same order as for the first scanned line. Progressively attenuation effects become greater. For the last scanned spray line the attenuation of the scattered light from droplets between the probed spray region and the camera can exceed 10% of the scattered light intensity and correction is required if accurate measurements are to be performed. In **Figure 14**, the raw intensity of the scattered light across the beam path is presented and in **Figure 15** the corrected spatial distribution is presented, which is clearly higher. As such the corrected scattering cross section of **Figure 16** is higher than the uncorrected scattering cross section of **Figure 17**.

The overall attenuation of the incident laser beam across the measured spray plane is presented in **Figure 18** and demonstrated significant attenuation that can be as high as 20% in the vicinity of the spray central axis. The overall map of attenuation of scattered light intensity of the probed droplets due to droplets that are along the optical path to the imaging system is presented in **Figure 19** and shows a symmetric spray, but the attenuation can be significant for droplets further away from the camera. However, following the application of the developed attenuation correction methodology for both the attenuation of the incident laser beam intensity that probes the spray and the attenuation of the scattered light intensity of the probed droplets due to droplets present along the optical path to the imaging system, **Figure 20** shows the corrected scattering coefficient along the spray plane, which demonstrates correctly an oblong spray cross section symmetric along the two normal axis. The uncorrected map of the scattering coefficient is presented in **Figure 21**. The differences, while substantial, are not apparent from the visual inspection of the two maps, which can lead to an erroneous conclusion and remain undetected, unless the developed correction procedure is applied. However, the absolute magnitude of the error is considerable and is shown in **Figure 22**. It can be as high as 2.5 and is more profound along the long axis of the spray cross section, where attenuation of the emitted signal is strongest. Considering that the maximum measured values of the scattering coefficient are in the region of 15-20, the uncertainty in the scattered light intensity measurements is in the range of over 10%, which demonstrates the necessity of the correction procedure.

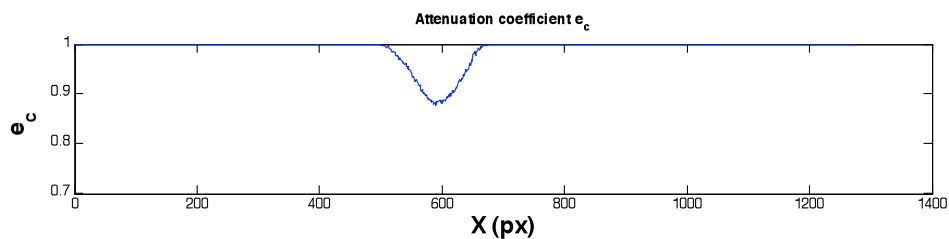


Figure 13: Spatial distribution of the attenuation coefficient e_c across the spray just before the last scanned beam. Spray centreline is at $X=600\text{px}$

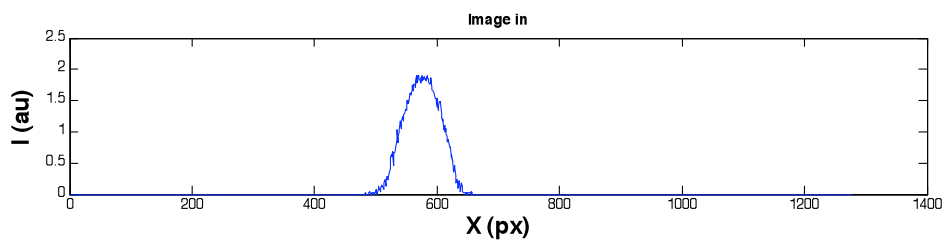


Figure 14: Spatial distribution of scattered light intensity across the spray for the last scanned beam. Spray centreline is at $X=600\text{px}$

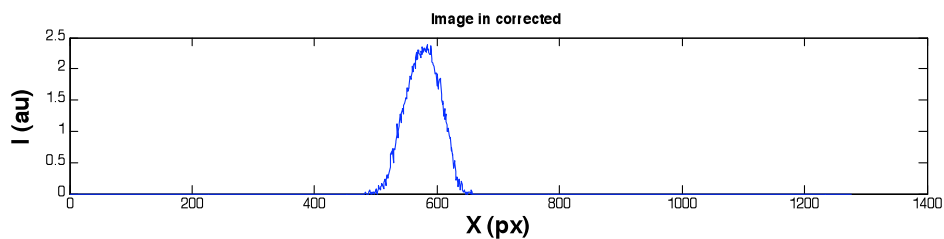


Figure 15: Spatial distribution of the corrected scattered light intensity across the spray for the last scanned beam. Spray centreline is at $X=600\text{px}$

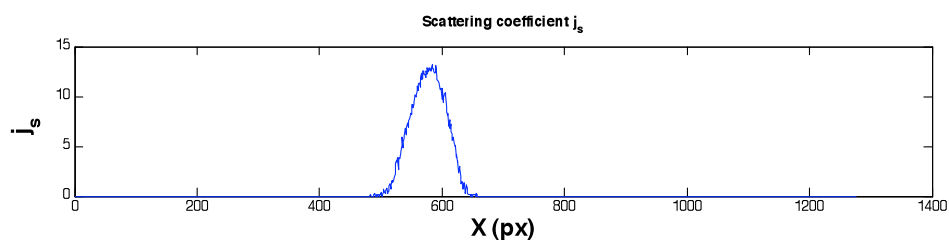


Figure 16: Spatial distribution of the corrected scattering coefficient σ across the spray for the last scanned beam. Spray centreline is at $X=600\text{px}$

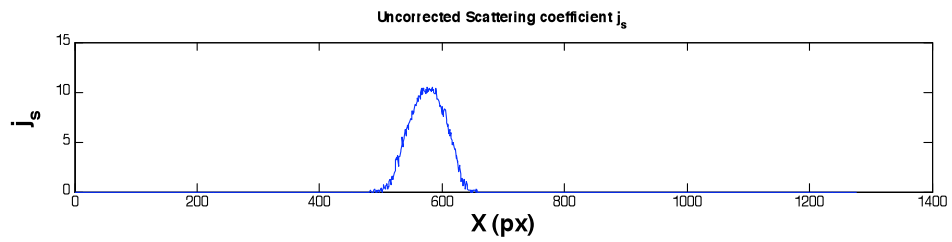


Figure 17: Spatial distribution of the uncorrected scattering coefficient σ across the spray for the last scanned beam. Spray centreline is at $X=600$ px

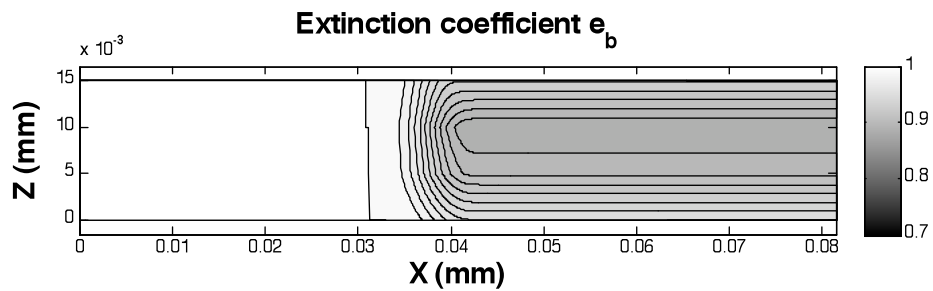


Figure 18: Extinction coefficient along the spray plane.

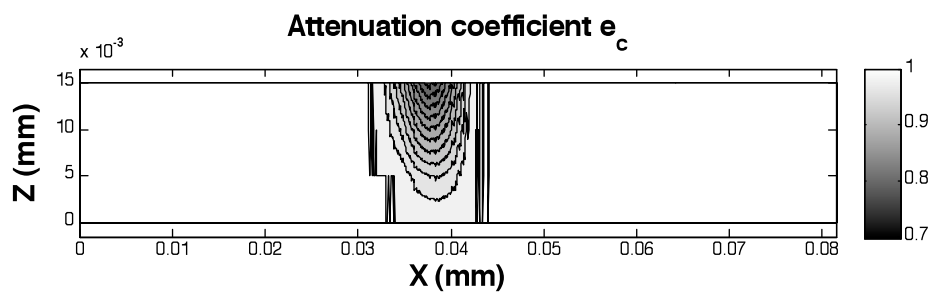


Figure 19: Attenuation coefficient along the spray plane.

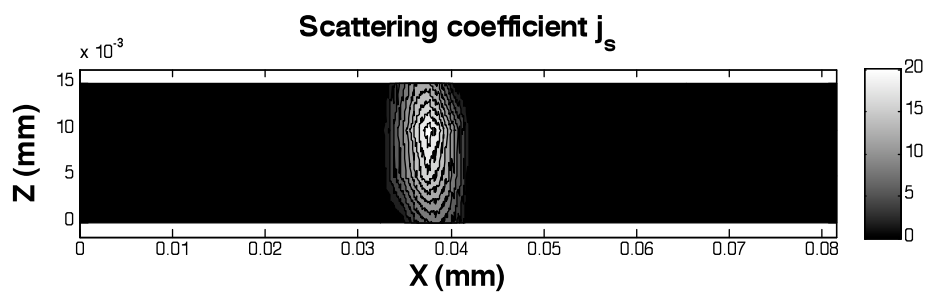


Figure 20: Corrected scattering coefficient along the spray plane.

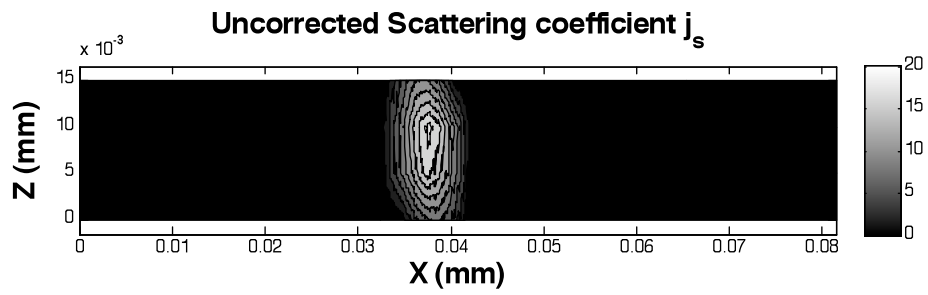


Figure 21: Uncorrected scattering coefficient along the spray plane.

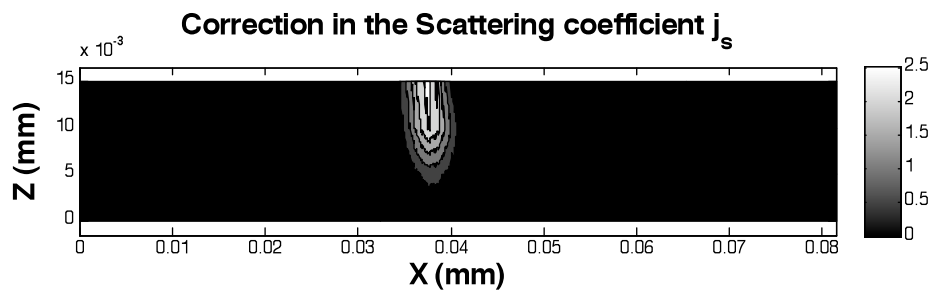


Figure 22: Correction of scattering coefficient along the spray plane.

Summary of findings

An investigation was undertaken to examine the application of a laser beam scanning methodology on the measurement of the time-averaged spray spatial structure. This approach can directly reduce secondary light scattering effects from the spray droplets and can take into account probe laser beam and scattered light intensity attenuation in order to reduce associated uncertainties on the spray characteristics.

Evaluation of two approaches was performed, where one considered scanning the probe laser beam across the spray and the other considered traversing the spray while the probing beam and the imaging optics were fixed. It is determined that for the purposes of evaluating the methodology for correcting quantitative measurement errors due to attenuation, the second approach is more appropriate. This is because scanning the beam would require constant refocusing of the imaging system to the probed region. Another issue is the changing imaging resolution as the distance between the probe laser beam and the imaging optics is constantly changing. By traversing the spray across the probe beam, both of the aforementioned effects are eliminated and the signal correction methodology can be applied directly.

The scattered light intensity correction methodology was successfully applied to a flat spray with measurements close to the nozzle and beam probing along the long dimension of the spray, so that attenuation effects are more profound. It is determined that attenuation of the laser beam along the spray can be as high as 20% and attenuation of the measured intensity signal can exceed 10%. Corrections can be made to address the attenuation effects and in the investigated spray the measurement error exceeds 10% especially at the regions of the spray further along the laser beam, where attenuation is strongest. This highlights the need for accounting for the attenuation effects of the laser beam and scattered light intensity for quantitative spray measurements.

References

- Berrocal, E., E. Kristensson, et al. (2012). "Quantitative imaging of a non-combusting diesel spray using structured laser illumination planar imaging." Applied Physics B-Lasers and Optics **109**(4): 683-694.
- Berrocal, E., E. Kristensson, et al. (2008). "Application of structured illumination for multiple scattering suppression in planar laser imaging of dense sprays." Optics Express **16**(22): 17870-17881.
- Berrocal, E., I. Meglinski, et al. (2005). "New model for light propagation in highly inhomogeneous polydisperse turbid media with applications in spray diagnostics." Optics Express **13**(23): 9181-9195.
- Brown, C., V. McDonell, et al. (2002). Accounting for laser extinction, signal attenuation, and secondary emission while performing optical patterning in a single plane. Proceeding of the 15th ILASS-America, Madison, USA.
- Charalampous, G. and Y. Hardalupas (2011a). "Method to reduce errors of droplet sizing based on the ratio of fluorescent and scattered light intensities (laser-induced fluorescence/Mie technique)." Applied Optics **50**(20): 3622-3637.
- Charalampous, G. and Y. Hardalupas (2011b). "Numerical evaluation of droplet sizing based on the ratio of the fluorescent and scattered light intensities (LIF/Mie technique)." Applied Optics **50**(9): 1197-1209.
- Charalampous, G. and Y. Hardalupas (2012). "Estimation of the droplet size spread with the laser induced fluorescence/Mie technique." Optics Letters **37**(11): 2040-2042.
- Czerwinski, M., J. Mroczka, et al. (2001). "Light-transmittance predictions under multiple-light-scattering conditions. I. Direct problem: hybrid-method approximation." Applied Optics **40**(9): 1514-1524.
- Czerwinski, M., J. Mroczka, et al. (2001). "Light-transmittance predictions under multiple-light-scattering conditions. II. Inverse problem: particle size determination." Applied Optics **40**(9): 1525-1531.
- Domann, R. and Y. Hardalupas (2001). "Spatial distribution of fluorescence intensity within large droplets and its dependence on dye concentration." Applied Optics **40**(21): 3586-3597.
- Domann, R. and Y. Hardalupas (2001). "A study of parameters that influence the accuracy of the Planar Droplet Sizing (PDS) technique." Particle & Particle Systems Characterization **18**(1): 3-11.
- Domann, R. and Y. Hardalupas (2003). "Quantitative measurement of planar droplet Sauter Mean Diameter in sprays using Planar Droplet Sizing." Particle & Particle Systems Characterization **20**(3): 209-218.
- Domann, R., Y. Hardalupas, et al. (2002). "A study of the influence of absorption on the spatial distribution of fluorescence intensity within large droplets using Mie theory, geometrical optics and imaging experiments." Measurement Science & Technology **13**(3): 280-291.
- Douglas, T., J. Verdick, et al. (1996). Accounting for laser sheet extinction in applying PLLIF to sprays. 34th Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics.
- Edwards, J. L., F.C. Gouldin, et al. (2003). High-speed absorption tomography with advanced reconstruction algorithms. 41st Aerospace Sciences Meeting & Exhibit, Reno, Nevada, 6-9 January 2003, AIAA 2003-1013.

- Kamimoto, T. (1994). Diagnostics of Transient Sprays by Means of Laser Sheet Techniques. COMODIA 94. Yokohama, Japan: 33-41.
- Kristensson, E., L. Araneo, et al. (2011). "Analysis of multiple scattering suppression using structured laser illumination planar imaging in scattering and fluorescing media." Optics Express **19**(14): 13647-13663.
- Kristensson, E., E. Berrocal, et al. (2011). "Extinction coefficient imaging of turbid media using dual structured laser illumination planar imaging." Optics Letters **36**(9): 1656-1658.
- Kristensson, E., E. Berrocal, et al. (2011). "Structured illumination for 3D Mie imaging and 2D attenuation measurements in optically dense sprays." Proceedings of the Combustion Institute **33**(1): 855-861
- Le Gal, P., N. Farrugia, et al. (1999). "Laser Sheet Dropsizing of dense sprays." Optics and laser technology **31**(1): 75-83.
- Sankar, S. V., K. E. Maher, et al. (1999). "Rapid characterization of fuel atomizers using an optical patternator." Journal of Engineering for Gas Turbines and Power-Transactions of the ASME **121**(3): 409-414.
- Sick, V. and B. Stojkovic (2001). "Attenuation effects on imaging diagnostics of hollow-cone sprays." Applied Optics **40**(15): 2435-2442.
- Su, J., M. Drake, et al. (1998). Towards Quantitative Characterization of Transient Fuel Sprays Using Planar Laser Induced Fluorescence Imaging. ILASS - Americas '98. Sacramento, CA.
- Yeh, C. N., H. Kosaka, et al. (1993). A fluorescence / scattering imaging technique for instantaneous 2-D measurements of particle size distribution in a transient spray. Proceedings of the 3rd Congress on Optical Particle Sizing. Yokohama, Japan: 355-361.
- Zimmer, L., R. Domann, et al. (2003). "Simultaneous laser-induced fluorescence and Mie scattering for droplet cluster measurements." AIAA Journal **41**(11): 2170-2178.